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Added-mass partitoned fluid-structure interaction solver for aorta disection blood flow

Željko Tuković*, Anja Horvat*, Lana Virag*, Philipp Milović+, Ivan Batistić*

**University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture*
E-mails: {zeljko.tukovic, anja.horvat, lana virag, ivan.batistic}@fsb.hr

+University of Zagreb, School of Medicine
E-mail: philipp.milovic@mef.hr

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1. Introduction

Loosely or strongly coupled Dirichlet-Neumann (DN) partitioned fluid-structure interaction (FSI) algorithms are stable only if the density of the structure is much higher than that of the fluid. This requirement is difficult to achieve in hemodynamics where the density of blood is on the same order of magnitude as the density of arterial walls. The stability issue is even more pronounced when the blood vessel walls are surrounded by the blood flow from both sides, as is the case for an aortic dissection.

2. Methods

The laminar flow of an incompressible Newtonian fluid (blood) is described by Navier Stokes equations in arbitrary Lagrangian-Eulerian form. On the other hand, deformation of incompressible neo-Hookean hyperelastic material (aortic wall) is defined by momentum equation in total Lagrangian form. Both fluid and solid models are spatially discretised using cell-centered finite volume method, whereas temporal discretisation is preformed by first order accurate Euler implicit scheme. FSI problem is solved using added-mass partitioned scheme, meaning the fluid sub-problem is solved with a Dirichlet boundary conditions (BC) for velocity (structure velocity) and Robin BC for pressure at the FSI interface, while the solid sub-problem is solved with a Neumann BC (fluid stress) at the interface. The stability of the scheme is ensured by the Robin BC for pressure, where the normal derivative of the pressure at the interface is defined by the reduced momentum equation, while the value of the pressure is bounded by solid inertia. In the original Robin BC, as defined in [1]:

$$p^k + \frac{\rho_S h_S}{\rho_F}\left(\frac{\partial p}{\partial n}\right)^k = p^{k-1} - \rho_S h_S \left(\frac{\partial v_n}{\partial n}\right)^{k-1}, \qquad (1)$$

the virtual thickness h_S is calculated using propagation speed of p-waves in an elastic media. Since p-wave speed is infinite in the case of incompressible solid, virtual thickness is set to local thickness of the structure. Such an approach seams appropriate in the case of shell-like structures such as blood vessel walls. In the case of internal elastic walls surrounded by fluid flow from both sides, we propose a modified Robin BC in a following form:

$$\left(p^k - p_o^k\right) + \frac{\rho_S h_S}{\rho_F}\left(\frac{\partial p}{\partial n}\right)^k = \left(p^{k-1} - p_o^{k-1}\right) - \rho_S h_S \left(\frac{\partial v_n}{\partial n}\right)^{k-1}, \qquad (2)$$

where p_o is the fluid pressure at the opposite side of the internal wall. This is taken into account implicitly during the solution of pressure equation.

3. Results

Proposed numerical model is tested on a wave propagation in an elastic tube test case intended to demonstrate the capability of the model to predict blood flow in large arteries. Two geometrical variants of the case are tested: standard *single tube case* [1] and modified *double tube case* which consists of an additional centrally positioned shorter internal tube. Both tubes are clamped at the inlet and outlet. During the first 0.003 s, a uniform over-pressure is applied at the inlet in both cases. Figures 1 and 2 shows fluid pressure field and solid equivalent stress field at time instance 0.005 s and Figure 3 shows convergence history of the applied FSI coupling algorithm. Double tube test case, which can be considered as a representative test case for the aorta dissection, requires twice as mach FSI coupling iterations, but number of iterations is still acceptable considering complexity of the problem.

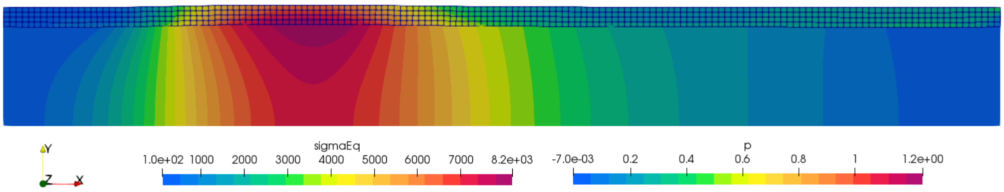

Figure 1. Single tube case; fluid pressure and solid equivalent stress at *t*=0.005 s

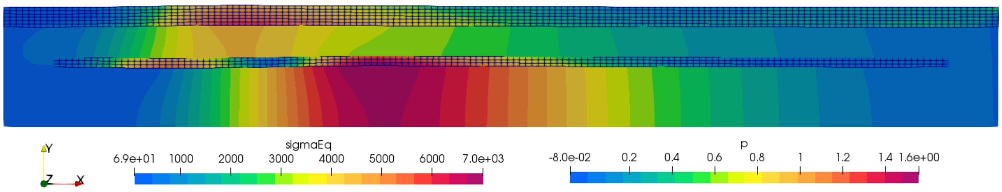

Figure 2. Double tube case; fluid pressure and solid equivalent stress at *t*=0.005 s

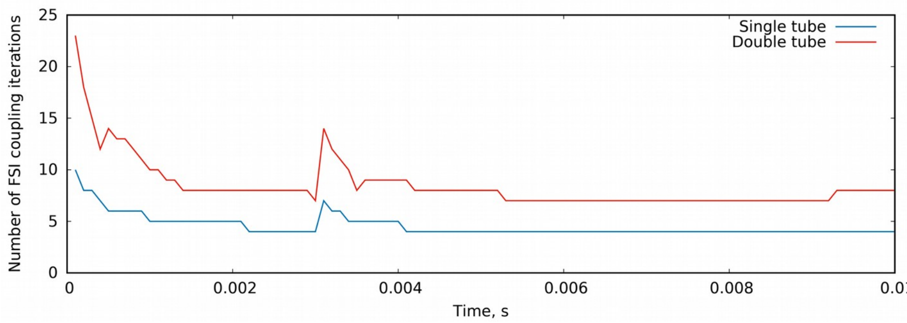

Figure 3. Convergence history; number of FSI coupling iterations as a function of time

4. Conclusions

It is proposed new added-mass partitioned FSI solution procedure based on Robin BC for pressure, which can handle incompressible solid and internal walls. There is no need for any under-relaxation during data transfer between fluid and solid analysis, which ensures good convergence of the solution procedure.

Acknowledgments

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References

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